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Pavement Rutting Dynamic Prediction Model

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Abstract: Rutting is one of major distresses affecting pavement performance. Most existing rutting models are based on a mechanistic-empirical (M-E) modeling approach or simply an empirical approach. M-E models use input parameters such as Poisson's ratio and either resilient modulus or dynamic modulus. Laboratory tests or other procedures conducted to determine these material parameters are expensive and time consuming. The cause of pavement deformation is very complicated and is affected by many variables, such as material properties, environmental conditions, and traffic loadings. Therefore, many of the models could not predict field data adequately. Thus, in this study, a pavement rutting dynamics prediction model (PRDPM) based on Grey System Theory is developed, based on rutting depth data obtained from laboratory tests. The developed model was verified using field test data obtained from domestic and other countries. The regression analysis results show that the predicted and measured value have more than 95% of linear relationship, and exhibit statistic significance. Therefore, the dynamic model can be used in Taiwan area with high degree of confidence. In addition, the model can predict rutting depths from the estimated traffic volumes to establish the threshold time for pavement maintenance, thus as a useful tool for pavement management system.

***Key words**: Grey system theory; Mechanistic-empirical (M-E) model; Permanent deformation; Rutting.*

Introduction

Rutting is one of the major distresses that affect flexible pavement performance. Permanent deformation on top of the pavement surface layer increases with increases in traffic loading and tire pressure [1]. A study [2] showed that 9, 45, 14, and 32% of the rutting have been observed in the subgrade, subbase, base, and surface layers, respectively. Most existing performance prediction models for rutting have been developed based on statistical analyses or mechanistic-empirical (M-E) modeling approach. However, pavement deformation is a very complex phenomenon and is affected by many variables, such as pavement structures, material properties, environmental conditions, and traffic loadings, etc. Therefore, many of the existing prediction models did not perform adequately.

The performance indicator used in M-E prediction models was compression strain on top of subgrade. Once the thickness of the pavement layers changed, as often the case in actual pavements, the parameters must be re-calculated. Thus, the accuracy of the prediction models has always been challenged. To improve the prediction accuracy, researches using different approaches or theories were carried out, such as the viscoelastic system computer program (VESYS) developed by the Federal Highway Administration (FHWA) of the United States, linear or nonlinear elastic and viscoelastic-plastic theory applications, and finite element method. However, most of the modeling approaches still had shortcomings. Many M-E models were not completely successful in explaining the relationship between the variation of pavement deformations and pavement response (*i.e.* vertical strain), asphalt mix properties, and climatic conditions. To further complicate the matter, behavior of pavement materials after loading is not homogeneous and isotropic, as commonly assumed in analysis. A study indicated that, after loading, Poisson's ratio of asphalt may be greater than 0.5 or even higher than 1.0 [3].

Statistical analyses were often used in developing pavement performance prediction models, and, in general, large amount of data are required for the models to be valid [4]. The VESYS system, for example, not only used mechanistic concepts to derive the prediction model, but also used a lot of data for statistical analyses [1].

As indicated in a study, regardless of what methods were utilized in developing the models, the following characteristics of the models should be recognized [5]:

1. Material properties need to be thoroughly analyzed by laboratory tests which are time consuming and expensive.
2. Materials used are limited by their availability in local areas that results in the use of different parameters in different areas.
3. Characterization of materials is based on, at least partially, ideal assumptions.
4. Discrepancies exist between predicted and field measured performance data.
5. Rutting is a complex phenomenon and is affected by too many variables.

Because of these concerns, a simple prediction model for permanent pavement deformation is proposed in this study that would serve as a useful tool for pavement engineers. As a result of recent advents of advanced laboratory facilities and pavement management systems, databases containing large amount of pavement materials and performance data have become available.

The stored data included pavement structures (layer thickness, number of lanes, etc.), material properties (asphalt elastic modulus, strength, etc.), pavement performance data (rut depth, cracking, etc.),

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traffic data, climatic data, and others. The availability of these data made the development of a prediction model possible. Efforts were expended to develop relationships between the rutting and the traffic loading, expressed as the Equivalent Single-Axial Load (ESAL), and other pavement parameters. The performance model was developed using Grey Modeling Method based on Grey System Theory. The modeling method, pavement rutting dynamics prediction model (PRDPM), was derived from laboratory test data and validated by field test data obtained from domestic and foreign countries.

Literature Review of Rutting Prediction Models

A pavement subjected to repeated traffic loading will produce vertical compression strain ε_c and result in permanent deformation as shown in Fig. 1. In previous researches, the vertical compression strain was calculated by muti-elastic theory for each layer of the pavement. These typical mechanistic based models developed by Asphalt Institute and Shell Petroleum are representative models and are very popular [6, 7]. A general form of permanent deformation failure model can be represented by Eq. (1). In this equation, N_d is the number of the repeated wheel load; ε_c is the compression strain on top of subgrade surface; and the coefficients of f_1 and f_2 are coefficients obtained from laboratory tests. Taking the general form, the following are some rutting prediction models developed by various organizations:

$$N_d = f_1(\varepsilon_c)^{-f_2} \tag{1}$$

1. Asphalt Institute [8]: $N_d = 1.365 * 10^{-9}(\varepsilon_c)^{-4.477}$
2. Shell Petroleum [6]: $N_d = 6.15 * 10^{-7}(\varepsilon_c)^{-4}$
3. Nottingham University [9]: $N_d = 1.13 * 10^{-6}(\varepsilon_c)^{-3.571}$
4. Mn/ROAD [10]: $N_d = 7.0 * 10^{15} * (\varepsilon_c)^{-3.909}$
5. U.S. Army Corps of Engineers [11]: $\varepsilon_c = 5.511 * 10^{-3} * (N_d)^{-0.1532}$

All the models derived were based on the compression strain of subgrade surface and ignore the effects of top layer deformation.

Typically, permanent deformation on the top layers of pavement (but not on the surface of the subgrade) would increase as traffic loading and tire pressure increased. Thus, FHWA developed a pavement analysis system, VESYS, which contained a simple model for rutting calculation. In this model, it was assumed that permanent deformation possessed a linear relationship with resilient strain as shown in Eq. (2) [12-14].

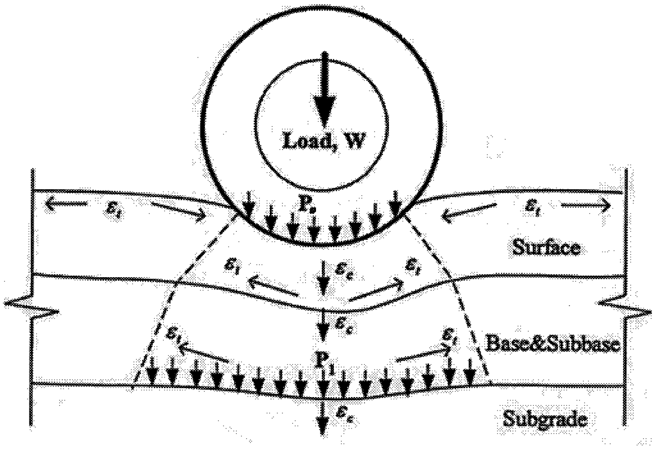


Fig. 1. Flexible Pavement Structural Deformation and Loading Distribution.

$$\varepsilon_p(N) = \mu\varepsilon N^{-a} \tag{2}$$

Where $\varepsilon_p(N)$: permanent strain after the N^{th} repeated wheel load,
μ : linear coefficient between permanent deformation and elastic or resilient strain,
ε : elastic or resilient strain after the 200th repeated wheel load,
N : numbers of repeated wheel load,
a : parameter of compression permanent deformation.

Because the VESYS system was not completely successful in explaining the permanent deformation, the system was revised based on dualaxial and triaxial wheel load analyses. Another rutting prediction model, Eq. (3) was developed by the Strategic Highway Research Program (SHRP) based on Eq. (2) [15, 16].

$$\varepsilon_p(N) = aN^b \tag{3}$$

Where $\varepsilon_p(N)$: permanent strain after the N^{th} repeated wheel load,
a : intercept of regression analysis,
N : numbers of repeated wheel load,
b : slope.

The models obtained might satisfy specific design or local needs. However, the efforts spent for determining properties of different materials used could be expensive and time consuming.

Development of the PRDPM

The causes of rutting had been shown to be very sophisticated. Before developing the model, the following are recognized:

1. The major cause of rutting is traffic loading.
2. Climatic conditions, such as temperature, moisture, etc., external force, and material properties cannot be completely controlled.
3. The technology of pavement measurement is sufficiently accurate.

Basic Concept

A system containing both insufficient (black) and sufficient (white) information is called a Grey System. The Grey System Theory deals with a system containing insufficient information; and the Grey Model (GM) is established by two important parameters, a development coefficient, a, and a control variable, b. The behavior of the forecasting sequence is dependent on the development coefficient, a. Through the process of building a prediction model, the different parameter values of a and b are conducted by different data sequences of measurement. Even though the prediction model is considered as the same data sequence, the variations of a and b influence the number of data that are required by the prediction model.

The Grey System Theory was proposed in 1982, and has been widely utilized in the prediction and decision-making fields [17, 18]. The system was developed to deal with poor, incomplete, and uncertain data that might be classified by five types of prediction fields: Time-Series, Calamity, Seasonal Calamity, Topological, and Systematic Forecasting [19]. The literature showed that there have been many successful applications in a variety of fields such as agriculture, earthquake, industry, and control [20-23]. However, there were few applications in the field of pavement modeling. In this study, the concept of Grey System Theory was introduced and rutting prediction models were derived. Equations of PRDPM were controlled by two factors: rut depth and number of loading cycles or traffic loading. The PRDPM procedure used a recursive approach for rut depth prediction. The process included (1) forecasting the accumulated rut depth following a number of loading cycles, (2) correcting the prediction with measured rut data, and (3) calculating the next prediction. Therefore, the performance of PRDPM depended on rut depth and number of loading cycles, which was represented by GM(1, 2), for first order degree of two variable factors.

Rutting Model Developed by Grey Method

The process of conducting PRDPM by GM(1, 2) is shown in the flow chart in Fig. 2 and the Grey Modeling Method is described as follows:

1. Let $x_1^{(0)}(k)=[x_1^{(0)}(1),x_1^{(0)}(2),x_1^{(0)}(3),...,x_1^{(0)}(n)]$ be a non-negative original sequence data representing rut depth data.
2. Taking the first-order accumulated generating operation (AGO) from $x_1^{(0)}(k)$ representing $x_1^{(1)}(k)$, where

$$x_1^{(1)}(k)=\sum_{i=1}^{k}x_1^{(0)}(i),\quad \forall k=1,2,3,\ldots,n \tag{4}$$

3. $Z_1^{(1)}(k)$ is the sequence of the mean of $x_1^{(1)}(k)$ and $x_1^{(1)}(k-1)$, where

$$Z_1^{(1)}(k)=0.5\ [x_1^{(1)}(k)+x_1^{(1)}(k-1)],\quad \forall k=2,3,\ldots,n \tag{5}$$

4. The grey differential equation of GM (1, 2) is described as

$$x_1^{(0)}(k)+aZ_1^{(1)}(k)=bx_2^{(1)}(k),\quad \forall k=2,3,\ldots,n \tag{6}$$

Where a = rutting development coefficient,
b = rutting control variable,
$x_1^{(0)}(k)$ = measured rut depth (mm),
$x_2^{(1)}(k)$ = AGO of $x_2^{(0)}(k)$,
$x_2^{(0)}(k)$ = log (number of loading cycles or ESAL)

5. The coefficient, a, and variable, b, are determined by the least-square method as following

$$\hat{P}=\begin{bmatrix}a & b\end{bmatrix}^T=(B^TB)^{-1}B^TY_N \tag{7}$$

Where

$$B=\begin{bmatrix}-Z_1^{(1)}(2) & x_2^{(1)}(2)\\ -Z_1^{(1)}(3) & x_2^{(1)}(3)\\ \vdots & \vdots\\ -Z_1^{(1)}(n) & x_2^{(1)}(n)\end{bmatrix}=\begin{bmatrix}-0.5(x_1^{(1)}(2)+x_1^{(1)}(1)) & x_2^{(1)}(2)\\ -0.5(x_1^{(1)}(3)+x_1^{(1)}(2)) & x_2^{(1)}(3)\\ \vdots & \vdots\\ -0.5(x_1^{(1)}(n)+x_1^{(1)}(n-1)) & x_2^{(1)}(n)\end{bmatrix};$$

$$Y_N=\begin{bmatrix}x_1^{(0)}(2)\\ x_1^{(0)}(3)\\ \vdots\\ \vdots\\ x_1^{(0)}(n)\end{bmatrix}$$

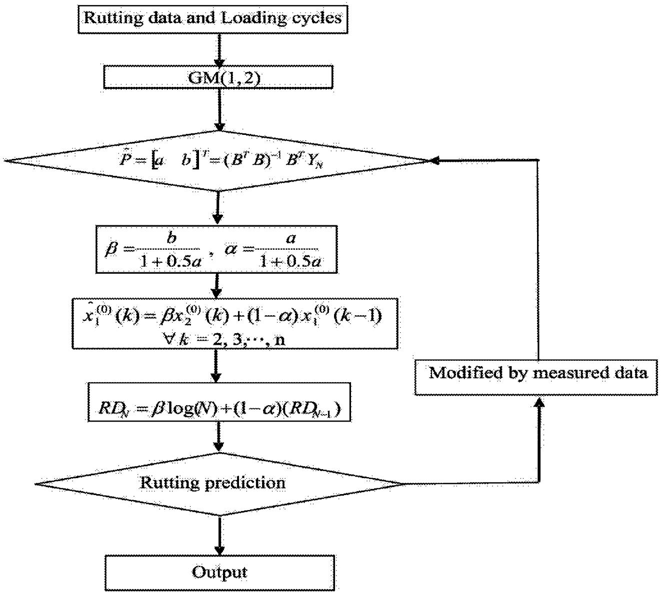


Fig. 2. Flow Chart for Developing PRDPM.

6. The GM(1, 2) solution is

$$\hat{x}_1^{(0)}(k)=\beta x_2^{(0)}(k)+(1-\alpha)x_1^{(0)}(k-1),\quad \forall k=2,3,\ldots,n \tag{8}$$

Where $\hat{x}_1^{(0)}(k)$ = predicted rut depth (mm),
$x_1^{(0)}(k)$ = measured rut depth (mm),
$x_2^{(0)}(k)$ = log (number of loading cycles or ESAL),
$\beta=\frac{b}{1+0.5a}$ and $\alpha=\frac{a}{1+0.5a}$: pavement variables.

7. The PRDPM can be rewritten as below

$$RD_N=\beta\log(N)+(1-\alpha)(RD_{N-1}) \tag{9}$$

Where RD_N = predicted rut depth at N^{th} loading cycles,
N = number of loading cycles,
(RD_{N-1}) = previous rut depth at $(N\text{-}1)^{th}$ measurement.

Laboratory Testing Evaluation

Permanent deformation tests were performed using the wheel tracking device. The device and associated test method was developed in Switzerland and then modified by the University of Hokkaido, Japan, designated as TR-322M. Test samples, with optimum asphalt contents determined by the Marshall Mix design, were fabricated by the rolling machine. Size of the samples was 300 x 300mm in section area and 50mm in height. Asphalt mix samples were subjected to wheel loads of 1.12, 1.65, and 2.18MPa at test temperatures of 60±1 and 25±1℃ under dry condition. The depth of deformation was measured at 100, 200, 400, 800, 1400, 1890, and 2520 loading cycles.

Two types of asphalt cements, AC-10 and AC-20, were used in the laboratory testing, which were obtained from a commercial petroleum company. The aggregate gradation used throughout the study was kept to be exactly at the mid band of the specification to satisfy the dense-graded HMA IVc gradation specification of the Ministry of Transportation and Communications (MTC, Taiwan), and 3/4" gradation specification of the ASTM D3515 and Superpave.

Table 1. Measured Rut Depth and Predicted Rut Depth (mm).

Asphalt type		AC-20		AC-20		AC-10		AC-10	
Test temperature		25℃		60℃		25℃		60℃	
Wheel load (MPa)	Number Of cycles	Measured rut depth	Predicted rut depth	Measured rut depth	Predicted rut depth	Measured rut depth	Predicted rut depth	Measured rut depth	Predicted rut depth
1.12	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.42	0.39	0.80	0.80	0.38	0.33	1.10	1.14
	200	0.67	0.69	1.50	1.47	0.60	0.65	1.70	1.68
	400	0.84	0.89	2.00	2.07	0.80	0.85	2.20	2.05
	800	1.12	1.05	2.60	2.54	1.12	1.05	2.20	2.39
	1400	1.30	1.26	3.60	3.05	1.26	1.31	4.70	2.53
	1890	1.38	1.42	4.00	4.21	1.33	1.41	5.90	6.04
	2520	1.47	1.49	4.80	4.54	1.37	1.45	7.60	7.68
1.65	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.50	0.38	1.80	1.25	0.60	0.59	2.50	1.93
	200	0.70	0.84	2.40	3.08	1.00	0.96	3.30	3.92
	400	1.00	1.06	3.60	3.81	1.10	1.24	4.30	4.75
	800	1.50	1.37	5.60	5.09	1.50	1.37	6.50	5.72
	1400	1.70	1.82	8.90	7.06	1.70	1.63	9.90	7.45
	1890	1.85	1.96	11.90	12.38	1.80	1.82	13.80	12.69
	2520	2.00	2.05	15.37	15.96	1.81	1.91	19.00	18.21
2.18	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.70	0.72	1.89	1.50	0.50	0.38	2.61	2.28
	200	1.20	1.14	2.83	3.28	0.70	0.90	3.63	4.03
	400	1.40	1.47	4.06	4.28	1.20	1.14	4.71	4.92
	800	1.70	1.66	5.95	5.51	1.70	1.66	6.31	5.85
	1400	2.00	1.88	9.06	7.24	1.90	2.18	10.59	6.99
	1890	2.10	2.12	11.53	11.83	2.00	2.23	14.28	13.58
	2520	2.20	2.22	16.40	14.62	2.10	2.24	19.29	18.77

Results of the testing are presented in Table 1. The model development process of PRDPM is illustrated here using rut depths measured for samples, with AC-20 asphalt, subjected to a wheel load of 1.12MPa at a test temperature of 25℃. Detail process is described as following:

1. Let measured rut depth: $x_1^{(0)}(k)=[0.00,\ 0.42,\ 0.67,\ 0.84,\ 1.12]$, $k=1,2,3,4,5$
2. Taking the first-order AGO from $x_1^{(0)}(k)$

$$\Rightarrow x_1^{(1)}(k)=[0.00,\ 0.42,\ 1.09,\ 1.93,\ 3.05], k=1,2,3,4,5 \tag{10}$$

3. $Z_1^{(1)}(k)=0.5\ [x_1^{(1)}(k)+x_1^{(1)}(k-1)]$

$$\Rightarrow Z_1^{(1)}(k)=[0.210,\ 0.755,\ 1.510,\ 2.49], k=2,3,4,5 \tag{11}$$

4. $x_1^{(0)}(k)+aZ_1^{(1)}(k)=bx_2^{(1)}(k)$

$$\Rightarrow \begin{bmatrix}0.42\\0.67\\0.84\\1.12\end{bmatrix}+a\begin{bmatrix}0.210\\0.755\\1.510\\2.490\end{bmatrix}=b\begin{bmatrix}2.00\\4.30\\6.90\\9.80\end{bmatrix} \tag{12}$$

Where

$x_2^{(0)}(k)=[0,\ \log(100),\ \log(200),\ \log(400),\ \log(800)]=[0,\ 2,\ 2.3,\ 2.6,\ 2.9]$, $k=1,2,3,4,5$;

$x_2^{(1)}(k)=\sum_{i=1}^{k}x_2^{(0)}(i)=[0.00,\ 2.00,\ 4.30,\ 6.90,\ 9.80],\quad k=1,2,3,4,5$

5. $$B=\begin{bmatrix}-0.210 & 2.00\\-0.755 & 4.30\\-1.510 & 6.90\\-2.490 & 9.80\end{bmatrix},\quad Y_N=\begin{bmatrix}0.42\\0.67\\0.84\\1.12\end{bmatrix}$$

$$\hat{P}=[a\quad b]^T=(B^TB)^{-1}B^TY_N=[0.540\quad 0.248]^T \tag{13}$$

6. $\beta=\frac{b}{1+0.5a}=0.195$, $\alpha=\frac{a}{1+0.5a}=0.425$

$$RD_N=0.195\log(N)+0.575(RD_{N-1}) \tag{14}$$

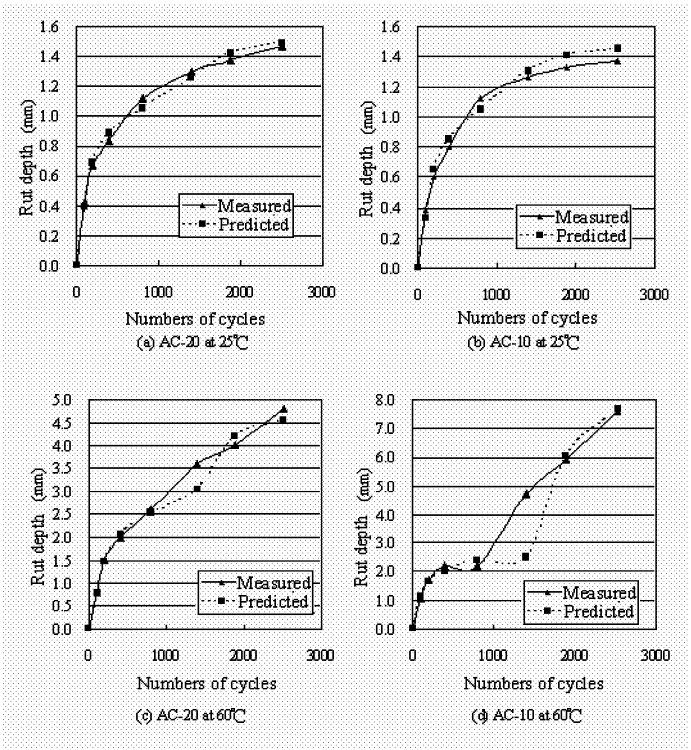
Five measurements of rut depths, starting from zero, were sufficient for the model development. From Eq. (14), the next number of cycles (the sixth cycle) and the 5th measured rut depths are 1400 and 1.12, respectively, and then, the 6th predicted data, RD_6, is 1.26. If the 6th measured rut depths is known, the model will be conducted by six data, k = 1 to 6, and the pavement variables of α and β will be modified by the matrix of the Eq. (13) in which the matrix of B and Y_N will be expanded by adding one row of data. Thus, the model will be as following:

$$B=\begin{bmatrix}-0.21 & 2.00\\-0.76 & 4.30\\-1.51 & 6.90\\-2.49 & 9.80\\-3.70 & 12.95\end{bmatrix},\quad Y_N=\begin{bmatrix}0.42\\0.67\\0.84\\1.12\\1.30\end{bmatrix},$$

$$\hat{P}=[a\quad b]^T=(B^TB)^{-1}B^TY_N=[0.472\quad 0.233]^T \tag{15}$$

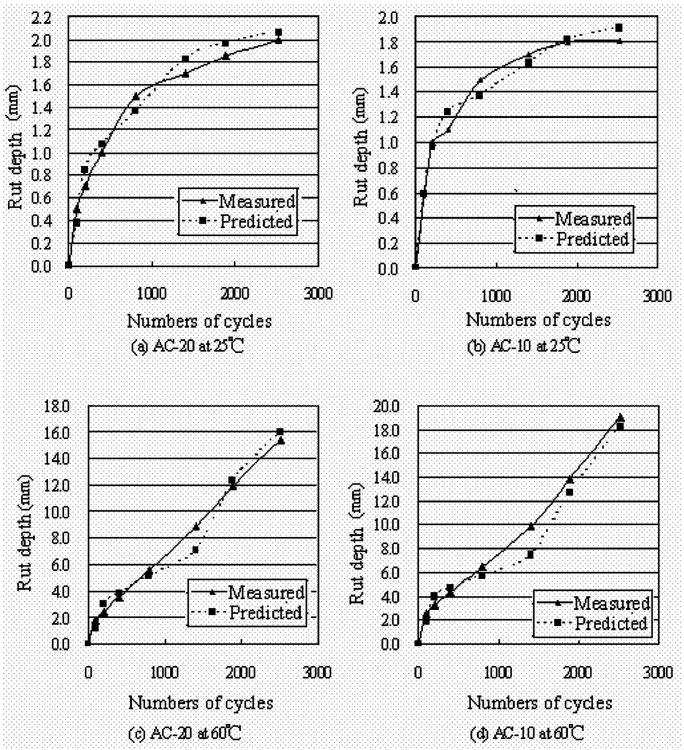
$$RD_N=0.189\log(N)+0.618(RD_{N-1}) \tag{16}$$

If the rut depth measured at the 1890 number of cycles are missing, the model can still predict the rut depth at the next number of cycles, 2520 (1.45mm in this case). This model development process was carried out for all testing and the completed data are



(a) AC-20 at 25℃ (b) AC-10 at 25℃ (c) AC-20 at 60℃ (d) AC-10 at 60℃

Fig. 3. Measured and Predicted Rut Depth at 1.12MPa.



(a) AC-20 at 25℃ (b) AC-10 at 25℃ (c) AC-20 at 60℃ (d) AC-10 at 60℃

Fig. 4. Measured and Predicted Rut Depth at 1.65MPa.

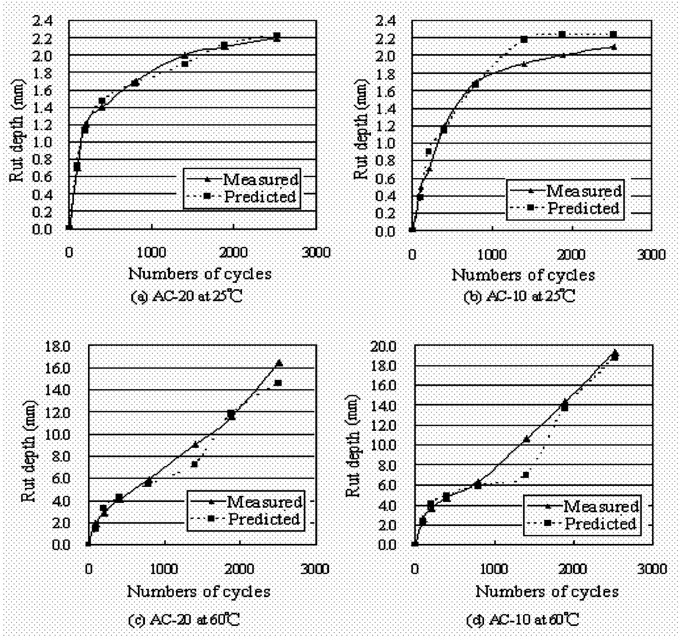
shown in Table 1 (including both the measured and the predicted rut depths). Comparisons of measured and predicted rut depths are shown in Figs. 3, 4, and 5 for samples tested under wheel load of 1.12, 1.65, and 2.18MPa, respectively. As can be seen, the PRDPM predicted rut depths are very close to those measured by the Wheel Tracking Device at different load levels and temperatures for all samples.

A statistical linear regression analysis was conducted to evaluate the accuracy of the predictions. In this analysis, the fitness of the model is defined by the coefficient of determination, R^2, which is a measure of how well the predicted data match the measured data. The R^2 values range from 0 to 1 or from 0 to 100%. A high R^2 value indicates that the variability of the dependent variable (rut depth in this case) can be successfully explained by the variations of the dependent variables considered in the model.

An F-test was also used to determine if the regression relationship between predicted rut depths and independent variables is significant to the proposed relationship between predicted and measured rut depths at a level of significance of 0.05.

Results from the regression analysis are summarized in Table 2. As can be seen, all of the R^2 values are close to 1.00 and p-values statistically significant. The p-values are much less than 0.05, indicating excellent prediction power of the model. In addition, regression coefficients at 95% confidence interval are calculated. The results show all of the confidence limits are between 0.648 and 1.264.

Generally, the predicted values have a certain amount of bias compared to the measured values. The tolerance of pavement roughness is ±0.3cm/3m according to the Specification of Highway Construction Technology issued by Taiwan Area National Freeway Bureau and ±0.25cm proposed in a research paper, respectively [5, 24]. The tighter tolerance level of ±2.5mm was chosen for this study. If the difference between the predicted and measured rut depths is within this tolerance level, it can be considered that the rutting prediction is sufficiently accurate. The comparison between measured and predicted rut depths within a tolerance level of ±2.5 mm is presented in Fig. 6. The results show that 95 of the 96 rutting predictions were within this tolerance level. Thus, it is believed that the PRDPM is useful for making predictions of rut depth.



(a) AC-20 at 25℃ (b) AC-10 at 25℃ (c) AC-20 at 60℃ (d) AC-10 at 60℃

Fig. 5. Measured and Predicted Rut Depth at 2.18MPa.

Validation of the Prediction Model with Field Test Data

Table 2. Statistical Regression Analysis Results (Predicted Rut Depth is the Dependent Variable).

Asphalt & Temperature	Wheel load (MPa)	R^2	Regression		Asymptotic standard error	Confidence interval (95%)	
			F	*P-Value*		Lower bound	Upper bound
AC-20 at 25℃	1.12	0.99	915.84	8.64E-08	0.0332	0.9221	1.0843
	1.65	0.98	329.34	1.80E-06	0.0573	0.8998	1.1803
	2.18	0.99	1042.34	5.87E-08	0.0306	0.9121	1.0617
AC-20 at 60℃	1.12	0.98	315.23	2.05E-06	0.0535	0.8191	1.0810
	1.65	0.98	256.47	3.77E-06	0.0633	0.8588	1.1685
	2.18	0.98	289.55	2.63E-06	0.0530	0.7717	1.0309
AC-10 at 25℃	1.12	0.99	619.98	2.76E-07	0.0422	0.9474	1.1539
	1.65	0.98	327.48	1.83E-06	0.0552	0.8645	1.1349
	2.18	0.99	271.12	3.20E-06	0.0668	0.9369	1.2640
AC-10 at 60℃	1.12	0.91	60.87	2.34E-04	0.1210	0.6481	1.2403
	1.65	0.98	299.01	2.40E-06	0.0533	0.7905	1.0512
	2.18	0.96	160.93	1.47E-05	0.0733	0.7500	1.1085

Table 3. National Highway No. 1 Field Test Data (mm).

Accumulated ESAL	Pen 40-50			Pen 60-70		
	Measured Rut Depth	Predicted Rut Depth	Residual Error	Measured Rut Depth	Predicted Rut Depth	Residual Error
1732735	7	5.60	1.40	8	6.11	1.89
2578549	7	9.20	-2.20	8	10.69	-2.69
3378746	10	9.30	0.70	11	10.81	0.19
4577453	11.5	10.89	0.61	14	12.59	1.41
6197109	12	11.75	0.25	15	14.38	0.62
9340772	12	12.40	-0.40	15	15.70	-0.70
Accumulated ESAL	Polymer-modified asphalt type I			Polymer-modified asphalt type II		
	Measured rut depth	Predicted rut depth	Residual error	Measured rut depth	Predicted rut depth	Residual error
1732735	6	4.39	1.61	5	3.82	1.18
2578549	6	8.14	-2.14	5	6.43	-1.43
3378746	8	8.22	-0.22	6	6.50	-0.50
4577453	11	9.53	1.47	8.5	7.08	1.42
6197109	11.7	11.44	0.26	8.5	8.42	0.08
9340772	11.8	12.42	-0.62	10	8.81	1.19

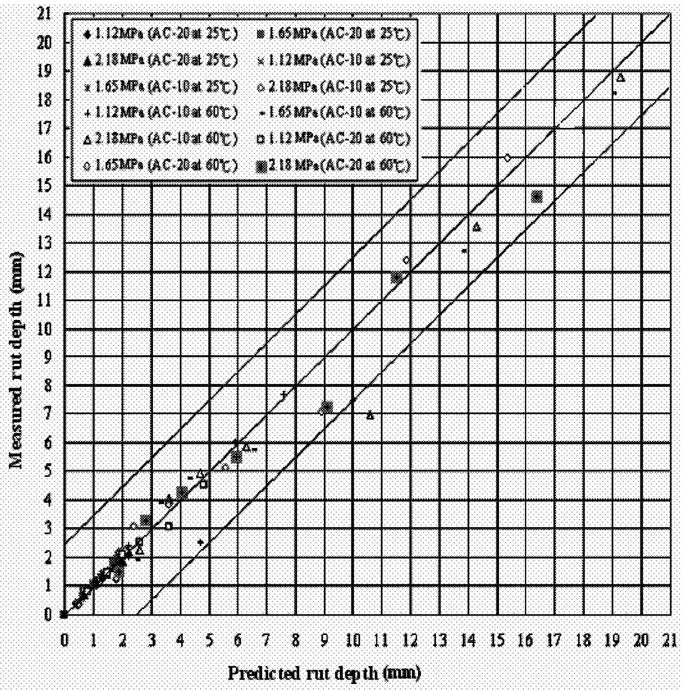


Fig. 6. Measured Versus Predicted Rut Depths.

In this study, field testing data of rutting were obtained to evaluate the prediction model and to confirm its validity.

Evaluation of Model Using Field Data Collected in Taiwan

Field measured rutting data were collected from National Highway No. 1 in Taiwan. Data were collected form pavements constructed with four different types of asphalts, Pen. 40-50, Pen. 60-70, and Polymer-Modified Asphalt type I and Polymer-Modified Asphalt type II for dense-grade hot mix asphalt and stone matrix asphalt, respectively. The number of traffic loading, in terms of accumulated 80-kN ESALs was calculated. The measured and predicted rutting data are shown in Table 3. It can be observed that 23 of the 24 predicted rutting values are within the tolerance of ±0.25cm, and the residual errors tends to decrease with increasing traffic volumes.

Regression analyses were also conducted to compare the predicted and field rutting data and the results are shown in Table 4. From this table, results indicate that R^2 values are all greater than 70% and F values are greater than the $F_{0.05}$ value of 7.70865. The regression analyses indicate that the linear regression relationship is statistically significant and, thus, the predicted and measured rut depths are well correlated.

Table 4. Statistical Regression Analysis of Field Test.

Asphalt type	R^2	Regression		Asymptotic standard error	Confidence interval (95%)	
		F	*P-Value*		Lower bound	Upper bound
Pen 40-50	0.75	11.969	0.0258	0.2578	0.1762	1.6080
Pen 60-70	0.77	13.497	0.0213	0.2439	0.2188	1.5729
Polymer-modified asphalt type I	0.77	13.103	0.0224	0.2495	0.2104	1.5960
Polymer-modified asphalt type II	0.71	9.767	0.0353	0.2268	0.0791	1.3387

Table 5. FHWA Field Test Results.

Number of cycles	#7			#8		
	Measured rut depth (mm)	Predicted rut depth (mm)	Residual error (mm)	Measured rut depth (mm)	Predicted rut depth (mm)	Residual error (mm)
1	0.8	0.8	0.00	1.4	1.4	0.00
10	2.5	2.7	-0.16	3.4	3.3	0.13
100	6.3	6.0	0.30	5.6	5.8	-0.21
500	8.7	8.9	-0.18	7.7	7.6	0.07
1000	10.1	10.3	-0.23	8.2	8.2	0.03
5000	13.6	12.4	1.22	9.1	10.3	-1.24
10000	14.9	14.8	0.10	10.7	10.8	-0.10
25000	17	16.4	0.58	11.3	11.5	-0.24
50000	18.3	18.2	0.12	14	12.3	1.73
75000	18.6	19.2	-0.62	15.3	12.6	2.70
100000	19.1	19.5	-0.44	16.2	14.3	1.88
120000	19.7	19.8	-0.14	18.3	15.7	2.64

Evaluation of Model Using Field Data Obtained Overseas

Field data were obtained from a research study conducted by the FHWA of the United States [25]. Data were randomly selected from one of the 15 sites (lane numbers 7 and 8 of site 1) subjected to Accelerated Loading Facility (ALF) at the Turner-Fairbanks Highway Research Center (TFHRC) in Mclean, Virginia. This field rutting tests was conducted under a loading stress of 44kN at 5.1m/s speeds without transverse wheel wander at temperatures from 40 to 76℃.

Comparisons between the predicted and measured rut depths are shown in Table 5, indicating variable results. However, the difference between observed and predicted rut depths for 22 of the 24 rutting data is less than ±2.5mm. As presented in Table 6, the regression analysis of the model is considered to predict the rut depth with sufficient accuracy.

Conclusions

One advantage of this modeling approach is the fact that it reduces parameters required in predicting rutting. Only two parameters, rut depth and number of loading cycles, are required. Other parameters, such as material properties, including Poisson's ratio, resilient modulus, dynamic modulus, vertical strain, asphalt mix properties, and ambient condition are removed from the prediction process. The function of PRDPM is to predict the rut depth of N^{th} loading cycles, if the previous rut depth data at $(N\text{-}1)^{th}$ loading cycles is measured. Based on the analysis performed, the following conclusions are presented:

1. Regression analysis results show high correlations between the predicted and measured rut depths, with R^2 values greater than 95%. Therefore, the dynamic model can be used in predicting rutting in the Taiwan area with high confidence.
2. The PRDPM can estimate the rutting depth from the anticipated traffic volume to determine the threshold time for maintenance, which can be a useful tool for pavement management system.
3. In order to fully evaluate the PRDPM model and validate its usefulness, it is recommended that future research should be carried out for further validate the model.

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Table 6. Statistical Regression Analysis of FHWA Field Test.

Section	R^2	Regression		Asymptotic standard error	Confidence interval (95%)	
		F	*P-Value*		Lower bound	Upper bound
#7	0.99	1939.879	8.75E-13	0.022741	0.950926	1.052265
#8	0.96	262.7528	1.66E-08	0.050479	0.705777	0.930726

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